NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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OPERATING CHARACTERISTICS OF AN ACCELERATION RESTRICTOR AS DETERMINED BY MEANS OF A SIMULATOR

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SUMMARY

The operating characteristics of an acceleration restrictor which limits the normal acceleration of an airplane in maneuvers were determined from tests on a simulator. The simulator consisted of a control stick geared to a magnetic brake unit and an analog computer which simulated the dynamic characteristics of the airplane. The restrictor was so designed that, when the brake control signal which was a function of various combinations of normal acceleration, pitching acceleration, and pitching velocity reached a certain preset value, the brake would stop the elevator motion. Tests were made to cover a wide range of airplane flight conditions and various types of brake-operating signals.

The results obtained for only three of the control signals tested are presented in this report. The first signal was the quantity normal acceleration plus the product of a gain constant and pitching acceleration; the second signal was the quantity normal acceleration, plus the product of a gain constant and pitching acceleration limited to positive values, plus the product of a gain constant and pitching velocity operated on by a canceling network; and the third signal was the same as the second except that the limitation on pitching acceleration was removed.

The results show that with the use of an acceleration restrictor, the response of an airplane to an abrupt elevator deflection can be controlled for a wide range of conditions. The second signal, which was the best of all those tried, gave ratios of peak to preset acceleration of the order of 1.1 to 1.4 for values of airspeed from 1,000 to 400 feet per second and for values of static margin from 20 to 3 percent mean aerodynamic chord. The third signal gave ratios of peak to preset acceleration up to about 1.4 for comparable inputs. Pilots manipulating the control stick of the simulator to approximate a rapid pull-up maneuver objected to the "coarse steps" in elevator motion caused by lag in the operation of the brake unit employed. However, by designing a brake unit with little lag in its operation, the undesirably large steps in elevator motion could be made smaller.

INTRODUCTION

In a previous paper (ref. 1) the need for acceleration restrictors was pointed out and an analysis of several simple devices to limit the maximum maneuvering acceleration of airplanes was presented. In reference 2, a more detailed analog-computer investigation of some of these devices was made. The devices considered in reference 2 work on the principle of stopping the elevator motion when a signal which is a function of the quantities normal acceleration, pitching acceleration, and pitching velocity reaches a certain value. The solutions obtained in reference 2, however, were somewhat idealized because the elevator control was assumed to move at a constant rate whenever it was not locked by the action of the acceleration restrictor. For this reason, it was considered desirable to extend the investigation to include a more realistic simulation of the elevator motion.

In the present investigation, control inputs were supplied to the analog computer by means of a control stick which simulated that of an airplane. Also, an actual braking device, consisting of a gear train and magnetic brake, was used to stop the elevator motion. Tests were made on the simulator to determine the operating characteristics of the restrictor through a wide range of airplane flight conditions for various types of brake-operating signals. Since the magnetic brake unit contributed considerable effective inertia to the control stick, the gearing ratio between the control stick and the brake was varied to study the effect of this inertia on the response characteristics. Several pilots operated the simulator so that their opinions on its behavior could be obtained.

It should be noted that the data obtained with the use of the simulator, the control stick of which was hand operated, should not be expected to give results as consistent as those obtained in reference 2 which made use of mathematically determined inputs.

SYMBOLS

a_n normal acceleration, g units

q pitching velocity, radians/sec

$\dot{q}$ pitching acceleration, radians/sec^2

K gain constant associated with $\dot{q}$, ft

K_1 gain constant associated with q, ft/sec

D differential operator, d/dt where t is real time

T time constant for pitching-velocity canceling network, sec

$$T_1 = \frac{KT}{K + K_1 T}$$

DESCRIPTION OF APPARATUS

Photographs of the control stick and brake unit used in the simulator are shown in figure 1. The commercially available electromagnetic brake, used to stop control-stick movement, incorporated a gear train through which the brake torque was multiplied to produce a torque rating of 9.34 foot-pounds. The brake, which operated on a 26-volt, 0.5-ampere supply, was designed so that it was normally in the locked condition, but unlocked when it was energized. The following brake characteristics, referred to rotation of the brake input shaft, were experimentally determined: static friction, 0.10 foot-pound; damping, 0.43 foot-pound per radian per second; inertia, 0.13 slug-feet^2. It was also experimentally found that the time lag in brake operation was of the order of 0.04 second when the brake was de-energized or locking and ranged from about 0.04 to about 0.10 second when the brake was energized or unlocking, depending on load applied and voltage. The backlash at the input shaft was about $\pm 1^{\circ}$.

The torque required of a magnetic brake for use with the acceleration restrictor may be reduced by gearing the brake to the control stick with a large gear ratio. The maximum gear ratio which may be used, however, is determined from consideration of the static friction, damping, or inertia contributed by the brake. In the present case, the inertia became critical before the other effects. In order to vary the inertia, three gear ratios between the rotation of the brake input shaft and the control stick were provided. These gear ratios were 3.2, 2.4, and 1.33 which corresponded to values of control-stick inertia of 1.35, 0.76, and 0.24 slug-feet^2.

The torque rating of the brake used in this investigation is considered much too small for use in an airplane installation with any of the gear ratios provided; however, the brake proved satisfactory for the analog-computer study if care was used to avoid applying unduly high stick forces. A shear pin was provided in the mechanism which would fail before the rating of the brake was exceeded. The rating of the brake was based on the strength of the gearing rather than on the slipping torque of the magnetic brake; thus, for the conditions investigated no slipping of the brake occurred.

The control stick was connected to a potentiometer which was used to apply control inputs to a Reeves Electronic Analog Computer (REAC). By varying the linkage between the control stick and the potentiometer, and the voltage across the potentiometer, the stick deflection per g was made equal to that existing on the simulated airplane for the various conditions of airspeed and static margin investigated. The gearing ratio between the control stick and elevator angle was assumed to be 1.0.

A pair of springs was attached to the control stick to provide a stick-force gradient. The moment arm of the springs about the pivot point of the stick could be varied to give the desired values of stick force per degree of stick deflection (or elevator deflection) for each of the four speeds tested. The simulated stick-force gradient was 3 pounds per g with a static margin of 10 percent of the mean aerodynamic chord. The stick force per degree of stick deflection was kept the same for the other center-of-gravity positions investigated and resulted in a value of stick force per g of 0.71 with a static margin of zero or 5.45 with a static margin of 20 percent of the mean aerodynamic chord.

In the design of an acceleration restrictor of this type for installation in an airplane, some provision must be made to permit the control stick to be moved at any time so as to relieve the acceleration. That is, since the control stick is locked by the brake whenever the control signal reaches the preset acceleration, the pilot would be unable to reduce the acceleration unless such a provision was made. This design feature was not incorporated in the present simulator because the operator could move the control stick by means of a switch that unlocked the brake.

DESCRIPTION AND SCOPE OF TESTS

A comprehensive series of tests were made on the simulator to determine the operating characteristics of the restrictor for various airplane flight conditions and for different brake-operating signals. The transfer functions of the typical fighter airplane used in this investigation were the same as those used for the fighter operating at sea-level conditions in references 1 and 2. These characteristic equations were set up in the REAC to simulate the dynamic characteristics of the airplane, and certain variables in the dynamic response of the airplane were used in various combinations to provide brake-operating signals. However, only representative results obtained with three brake-operating signals are presented in this report. A detailed discussion of the development and choice of the first two signals used herein may be seen in reference 2.

The first of these signals was the quantity $a_n + \frac{K}{g}\dot{q}$ while the second was the quantity

$$a_n + \begin{Bmatrix} \frac{K}{g}\dot{q} \text{ for } \dot{q} > 0 \\ 0 \text{ for } \dot{q} < 0 \end{Bmatrix} + \frac{K_1}{g} q \frac{TD}{1 + TD}$$

In the case of the second signal, the pitching-acceleration part of the signal was limited to positive values and the pitching-velocity part of the signal was operated on by the transfer function $\frac{TD}{1 + TD}$ in order to cancel out the signal due to the steady-state value of pitching velocity; that is, the canceling network effectively filtered out the low-frequency pitching-velocity signal while not affecting the signal at the higher frequencies. By a method of trial and error, a time constant T of 0.25 second and a gain constant K_1 of 644 feet per second was found to provide a satisfactory cancellation of the pitching-velocity signal.

In order to produce the second signal, three separate instruments and accessories would be required: a linear accelerometer, an angular accelerometer, and a rate gyro. In an attempt to simplify the instrumentation, it was proposed that the limitation on pitching acceleration be removed so that the pitching velocity q could be obtained by electrical integration of the pitching acceleration $\dot{q}$ rather than from a rate gyro. This meant that the last two terms in the signal could be combined and would result in a signal which was a function only of normal acceleration and pitching acceleration; thereby, the need for the rate gyro is eliminated. By eliminating the restriction on $\dot{q}$, the second signal may be written as

$$a_n + \frac{K}{g}\dot{q} + \frac{K_1}{g}(Dq)\frac{T}{1 + TD}$$

The third signal was obtained from this second signal by combining and rearranging to give

$$a_n + \frac{\dot{q}}{g}(K + K_1 T)\frac{T_1 D + 1}{TD + 1}$$

where $Dq = \dot{q}$ and $T_1 = \frac{KT}{K + K_1 T}$. The third signal, therefore, was equivalent to the second signal with the limitation on pitching acceleration removed.

Throughout most of this investigation, the control stick was moved as fast as possible. For the types of acceleration restrictors considered herein, the highest rates of elevator movement would produce the greatest tendency to exceed the preset acceleration and therefore be of most interest. Some tests with slow rates of stick motion are included for comparison. Also, a preset acceleration of 6g was used for the entire series of tests; that is, whenever the brake-operating signal exceeded a value of 6g, the brake would lock the control stick and the stick could not move until the signal fell below 6g.

RESULTS AND DISCUSSION

The results obtained from the simulator for the three brake-operating signals are presented in figures 2 to 8. The effects of static margin, airspeed, stick inertia, elevator rate, and gain constant on the response of the airplane with the acceleration restrictor controlled by the first signal $a_n + \frac{K}{g} \dot{q}$ are shown in figures 2 to 5. The results are presented as time histories of elevator angle and normal acceleration. The pitching velocity and the control signal are also shown in figure 2. The effects of static margin and airspeed on the response of the airplane with the restrictor controlled by the second signal

$$a_n + \begin{Bmatrix} \frac{K}{g} \dot{q} \text{ for } \dot{q} > 0 \\ 0 \text{ for } \dot{q} < 0 \end{Bmatrix} + \frac{K_1}{g} q \frac{TD}{1 + TD}$$

are shown in figures 6 and 7. The results here are presented as time histories of elevator angle and normal acceleration, with the pitching velocity as modified by a canceling network $\left(q \frac{TD}{1 + TD}\right)$ and the control signal also included in figure 6. Figure 8 shows the effect of airspeed on the response of the airplane with the restrictor controlled by the third signal

$$a_n + \frac{\dot{q}}{g} (K + K_1 T) \frac{T_1 D + 1}{TD + 1}$$

The results in this case (designated "unlimited" in key of fig. 8) are presented as time histories of elevator angle, normal acceleration, and the control signal and are compared with the corresponding results obtained with the second control signal (designated "limited" in key). The results should be interpreted on the basis that an ideal acceleration restrictor of this type should be capable of providing a constant ratio of peak acceleration to preset acceleration of 1.0 thoughout the speed range and for a large range of static margins.

Brake-Operating Signal $a_n + \frac{K}{g} \dot{q}$

Figure 2 indicates that in the zero-static-margin case the acceleration exceeded the preset value of 6g by a large amount; in fact, the restrictor controlled by the first signal was unable to stop the elevator soon enough to prevent the acceleration from reaching a value of about 17g. (At zero static margin, the maneuver margin was 3.3 percent of the mean aerodynamic chord.) As the static margin was increased, the restrictor was able to control the maximum value of elevator angle that was reached in each case so that the maximum value of acceleration above the preset value of 6g was materially reduced. The effect of lag in the operation of the brake may be seen by noting the time at which the signal becomes greater or less than the preset value and the corresponding locking and unlocking of the elevator. It should also be noted that the brake locks the elevator after the signal exceeds 6g somewhat faster than it unlocks the elevator after the signal falls below 6g. The rather "coarse steps" in elevator deflection can be directly attributed to the lag in brake operation.

Figure 3 shows that for a static margin of 10 percent mean aerodynamic chord, the ratio of peak acceleration to preset acceleration increased from about 1.4 at an airspeed of 400 feet per second to about 2.7 at an airspeed of 1,000 feet per second. This large variation in acceleration was due to the fact that the last increment in elevator deflection caused by the finite time lag in brake operation produced proportionally larger values of acceleration as the speed was increased.

Increasing the inertia of the control stick from 0.24 to 1.35 slug-feet^2 (see fig. 4) caused somewhat longer response times because it required more time to start the elevator moving from a constant deflection. However, the maximum values of acceleration that were reached were only slightly affected.

The effects of elevator rate are shown in figure 5(a). For the slow rates of elevator motion, the brake was able to lock the elevator at the deflection required to obtain a maximum value of acceleration fairly close to the preset acceleration.

Changing the gain constant of pitching acceleration K from 154.7 feet to 88.1 feet (fig. 5(b)) noticeably increased the value of peak acceleration obtained. Obviously, the larger value of gain was more desirable. In practice, the gain constant of the pitching acceleration that could be employed might be limited because of the pitching accelerations caused by rough air.

In an effort to improve the operating characteristics of the acceleration restrictor, especially in regard to the large variation in the ratio of peak acceleration to preset acceleration with speed, a series of tests were made to determine a better brake-operating signal. During these tests, described in reference 2, it was found that by adding a signal proportional to pitching velocity to the control signal, the acceleration-limiting characteristics of the restrictors were greatly improved. The results obtained with this control signal, referred to previously as the second signal, are described in the following section.

$$\text{Brake-Operating Signal} \quad a_n + \begin{Bmatrix} \frac{K}{g}\,\dot{q} \text{ for } \dot{q} > 0 \\ 0 \text{ for } \dot{q} < 0 \end{Bmatrix} + \frac{K_1}{g}\,q\,\frac{TD}{1 + TD}$$

As shown in figure 6, the restrictor controlled by the second signal effectively limited the acceleration obtained for static margins as low as 3 percent of the mean aerodynamic chord, and there was little or no overshoot in acceleration beyond the steady-state values for the entire range of static margins tested. The steady-state values of acceleration ranged from about 6.8g to 8.3g for static margins from 20 to 3 percent of the mean aerodynamic chord; thus, the ratios of peak acceleration to preset acceleration were about 1.1 to 1.4.

The effects of speed on the response of the simulated airplane for a static margin of 10 percent mean aerodynamic chord are shown in figure 7. Here again, little if any overshoot in acceleration occurred beyond the steady-state values for the speed range tested. The steady-state values of acceleration ranged from about 6.3g to 6.9g for airspeeds from 1,000 to 400 feet per second, corresponding to ratios of peak to preset acceleration of about 1.05 to 1.15.

It should be pointed out that this signal was the best of the many combinations tried from the standpoint of limiting the acceleration for the widest range of airplane flight conditions. However, to determine the feasibility of simplifying the instrumentation for an actual airplane installation, the following section presents typical results obtained with the third signal.

$$\text{Brake-Operating Signal} \quad a_n + \frac{\dot{q}}{g}\left(K + K_1 T\right)\frac{T_1 D + 1}{TD + 1}$$

The effects of airspeed on the response of the simulated airplane with the acceleration restrictor controlled by the third signal are shown in figure 8. As was expected, removing the limitation on pitching acceleration allowed the stick, and therefore the normal acceleration, to attain somewhat higher values than those with the limitation. Generally, the value of normal acceleration for the unlimited case was on the order of 0.5g larger than the value for the limited case with comparable inputs. The larger values of normal acceleration shown in figure 8 for the limited case, when compared with those of figure 7, can be attributed to the higher rates of elevator application used in the present case. From this example, therefore, it is obvious that the degree of signal simplification that can be tolerated depends on the amount of control of maximum acceleration that is required. In the present case (fig. 8), ratios of peak to preset acceleration of the order of 1.4 can be expected for elevator rates similar to those in figures 6 and 7.

Pilot Operation of Restrictor

Response time.- Since an acceleration restrictor should not appreciably increase the response time of the airplane, a test was made on the simulator with the restrictor inoperative to obtain data for purposes of comparison with those obtained with the restrictor operative. In this test, a pilot attempted to make a rapid pull-up to a steady-state acceleration of 6g. In performing the pull-up, the pilot rapidly pulled the stick back and then pushed it forward a little so that after reaching an acceleration of about 8g the steady-state value became about 6g. It was found that the time to peak acceleration was of the order of 1 second and, for the corresponding restricted case (fig. 6, 20 percent mean aerodynamic chord), was about 2.2 seconds. Whether the increase in response time caused by the restrictor would prove objectionable is not known. Only a flight investigation of the airplane with and without the acceleration restrictor installed can provide a realistic evaluation of the resticto r.

Comments.- Several pilots were asked to manipulate the simulator's control stick in such a manner as to approximate an actual pull-up maneuver. On the whole, the pilots found this maneuver difficult because of the lack of "feel" of acceleration. Also, they objected to the "coarse steps" in moving the stick, in that, since force was continually applied to the stick, the sudden release of the brake caused some discomfort. Nevertheless, all the pilots agreed that an acceleration restrictor of the type described herein might be desirable in an airplane and warranted a flight investigation. In fact, the pilots thought it highly likely that with the restrictor properly installed they, knowing that the restrictor would prevent any overloads on the airplane, would tend to use faster rates of elevator motion so as to perform the fastest possible maneuvers.

CONCLUSIONS

The operating characteristics of an acceleration restrictor were determined from tests on a simulator consisting of a control stick geared to a magnetic brake and an analog computer. The restrictor worked on the principle of stopping the elevator motion by means of a brake when a signal which was a function of normal acceleration, pitching acceleration, and pitching velocity reached a certain preset value. Data from only three of the brake-operating signals investigated are presented herein.

1. The results obtained with the first of these signals, which was the quantity normal acceleration plus the product of a gain constant and pitching acceleration, were as follows: Large undesirable variations in the ratio of peak acceleration to preset acceleration occurred with changes in speed and static margin. Increasing the inertia of the control stick from 0.24 to 1.35 slug-feet^2 caused somewhat larger response times but only slighly affected the maximum values of acceleration; the slower the control stick was moved, the closer the maximum acceleration approached the preset value.

2. The second signal (the best of all those tried) was the quantity normal acceleration, plus the product of a gain constant and pitching acceleration limited to positive values, plus the product of a gain constant and pitching velocity operated on by a canceling network. The results obtained with this signal showed that at an airspeed of 600 feet per second the ratios of peak acceleration to preset acceleration varied from about 1.1 to 1.4 for static margins from 20 to 3 percent mean aerodynamic chord. At a static margin of 10 percent mean aerodynamic chord, the ratios of peak to preset acceleration varied from about 1.05 to 1.15 for airspeeds from 1,000 to 400 feet per second.

3. The third signal was the same as the second with the limitation on pitching acceleration removed. This signal was investigated with the idea of simplifying the instrumentation and at the same time providing adequate control of the maximum acceleration. The results show that the maximum values of acceleration were of the order of 0.5g larger than those obtained with the second signal for comparable inputs.

4. Several pilots, performing rapid pull-up maneuvers with the simulator, objected to the "coarse steps" in elevator motion caused by the lag in brake operation. It is believed that by designing a brake with little lag in its operation, the undesirably large steps in elevator

motion could be made smaller and at the same time the ratios of peak to preset acceleration could be reduced. However, in order to evaluate properly an acceleration restrictor of the type described in this paper, a flight research program would be required.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., September 14, 1954.

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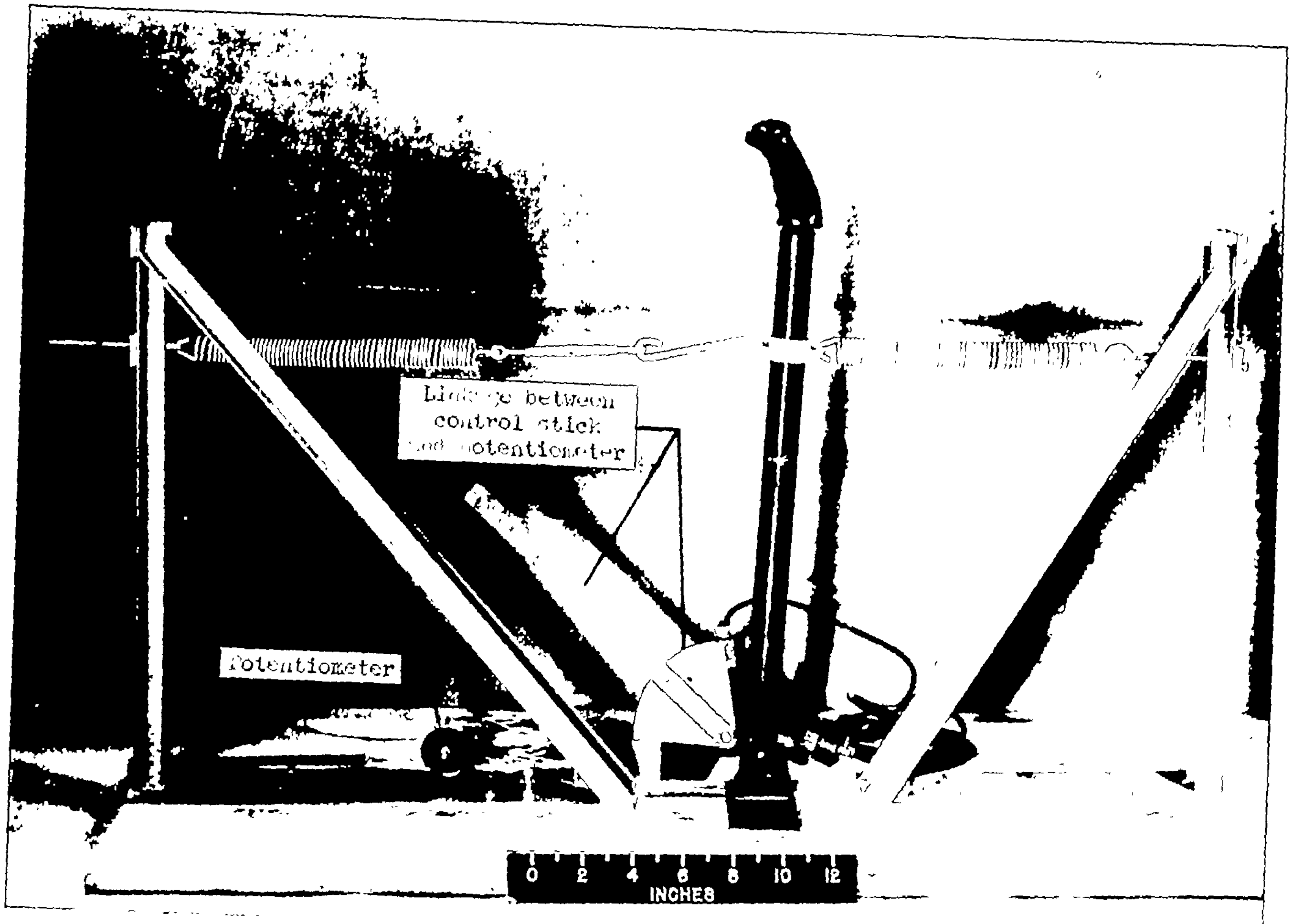
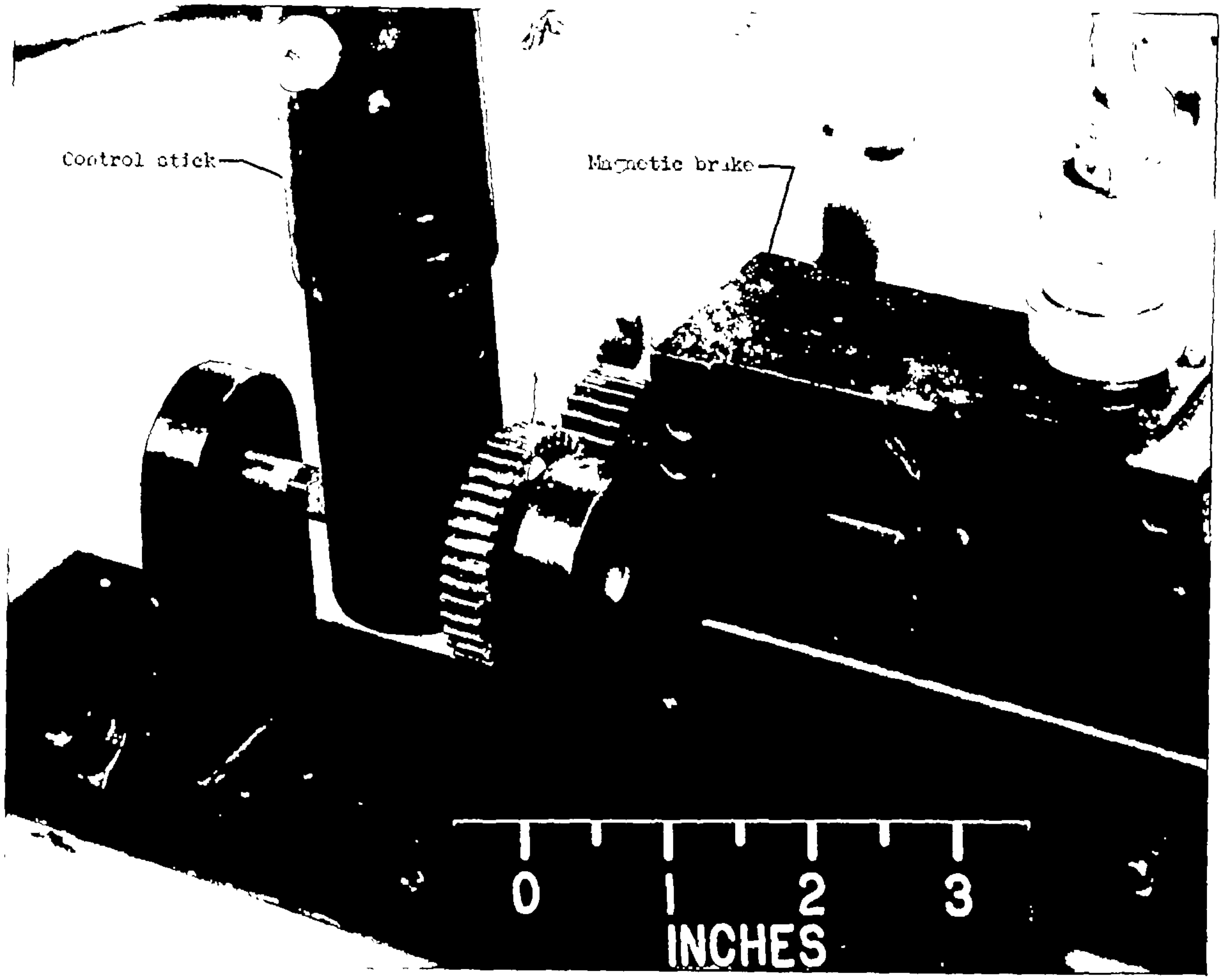
2. Kraft, Christopher C., Jr.: Theoretical Analysis of an Acceleration Restrictor Controlled by Normal Acceleration, Pitching Acceleration, and Pitching Velocity. NACA TN 3243, 1954.



(a) Side view. L-83155.1

Figure 1.- Photographs of the control stick and brake unit used in the simulator.



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(b) Close-up rear view.

Figure 1.- Concluded.

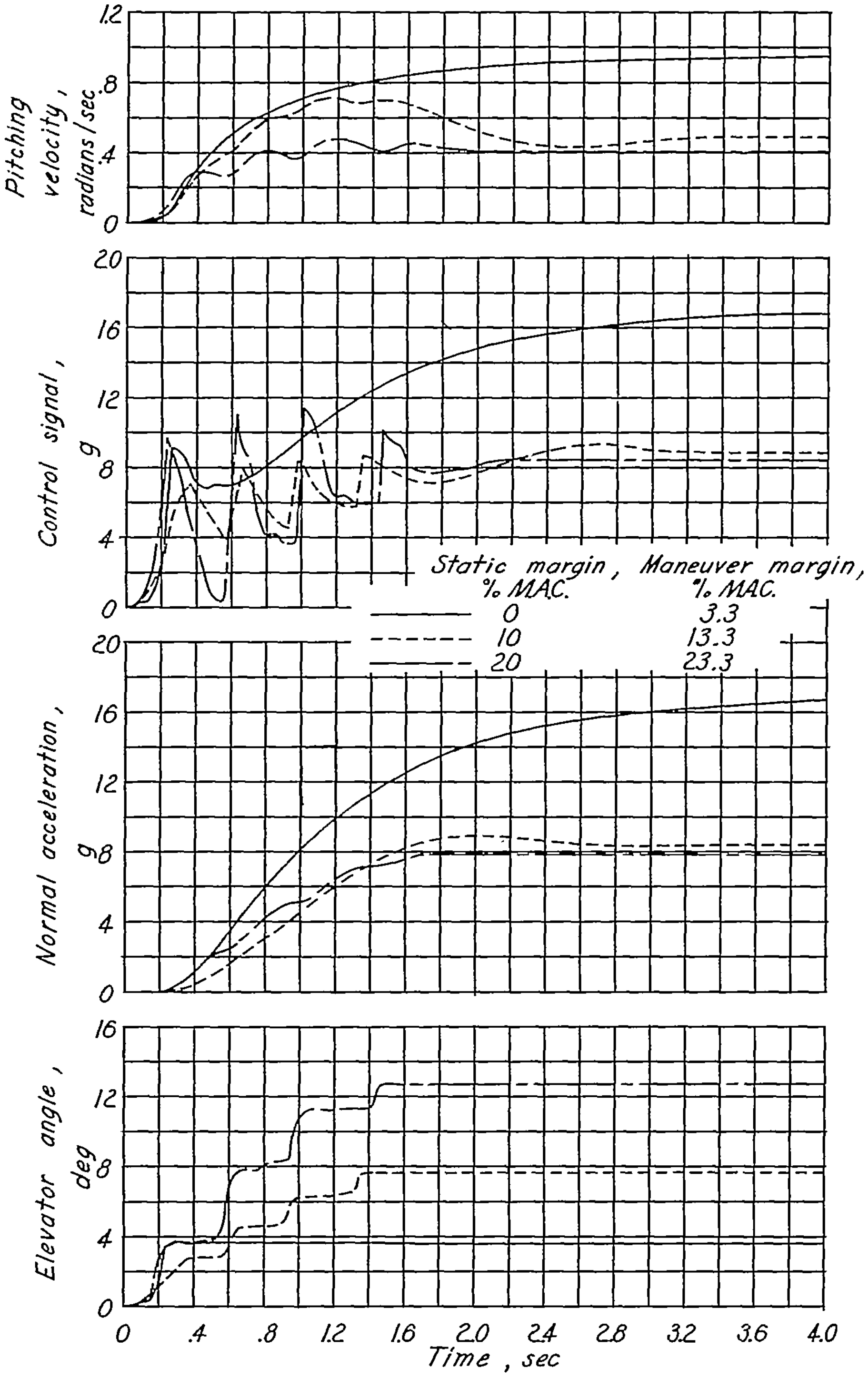


Figure 2.- Effects of static margin on the response of the airplane with the acceleration restrictor controlled by the signal $a_n + \frac{K}{g} \dot{q}$. Airspeed, 600 feet per second; stick inertia, 0.24 slug-feet^2; K = 154.7 feet.

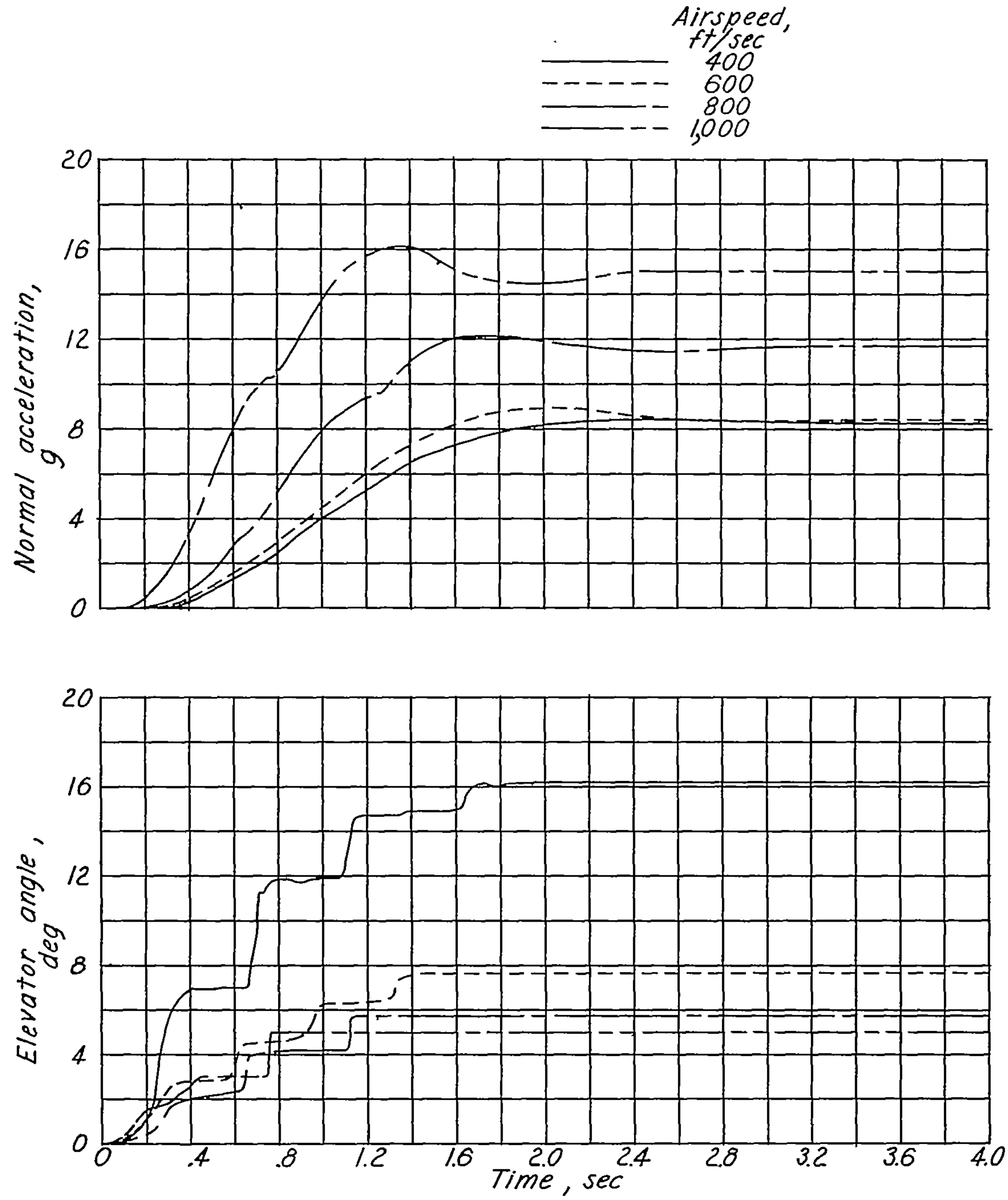


Figure 3.- Effects of airspeed on the response of the airplane with the acceleration restrictor controlled by the signal $a_n + \frac{K}{g}\dot{q}$. Static margin, 10 percent M.A.C.; stick inertia, 0.24 slug-feet^2; K = 154.7 feet.

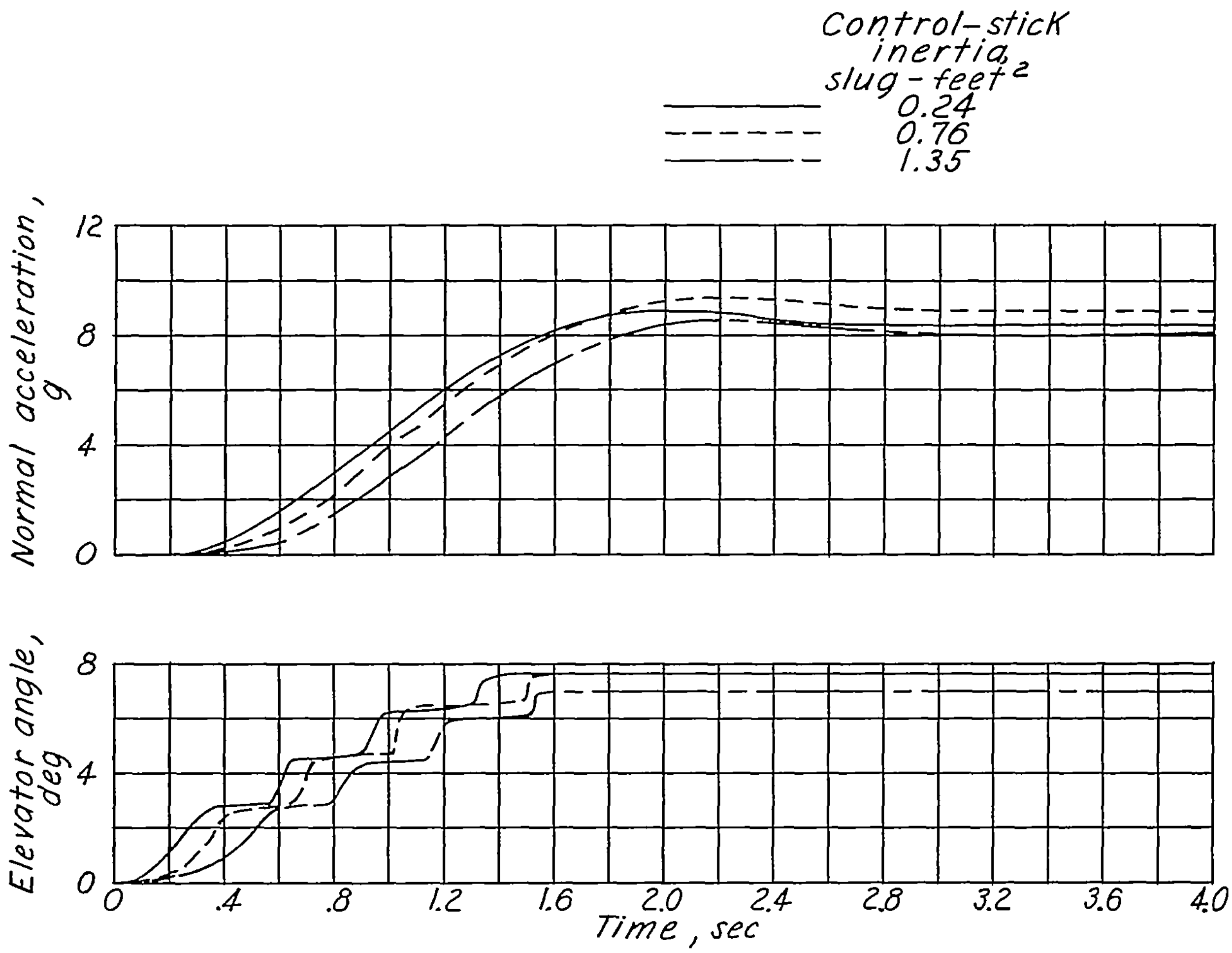
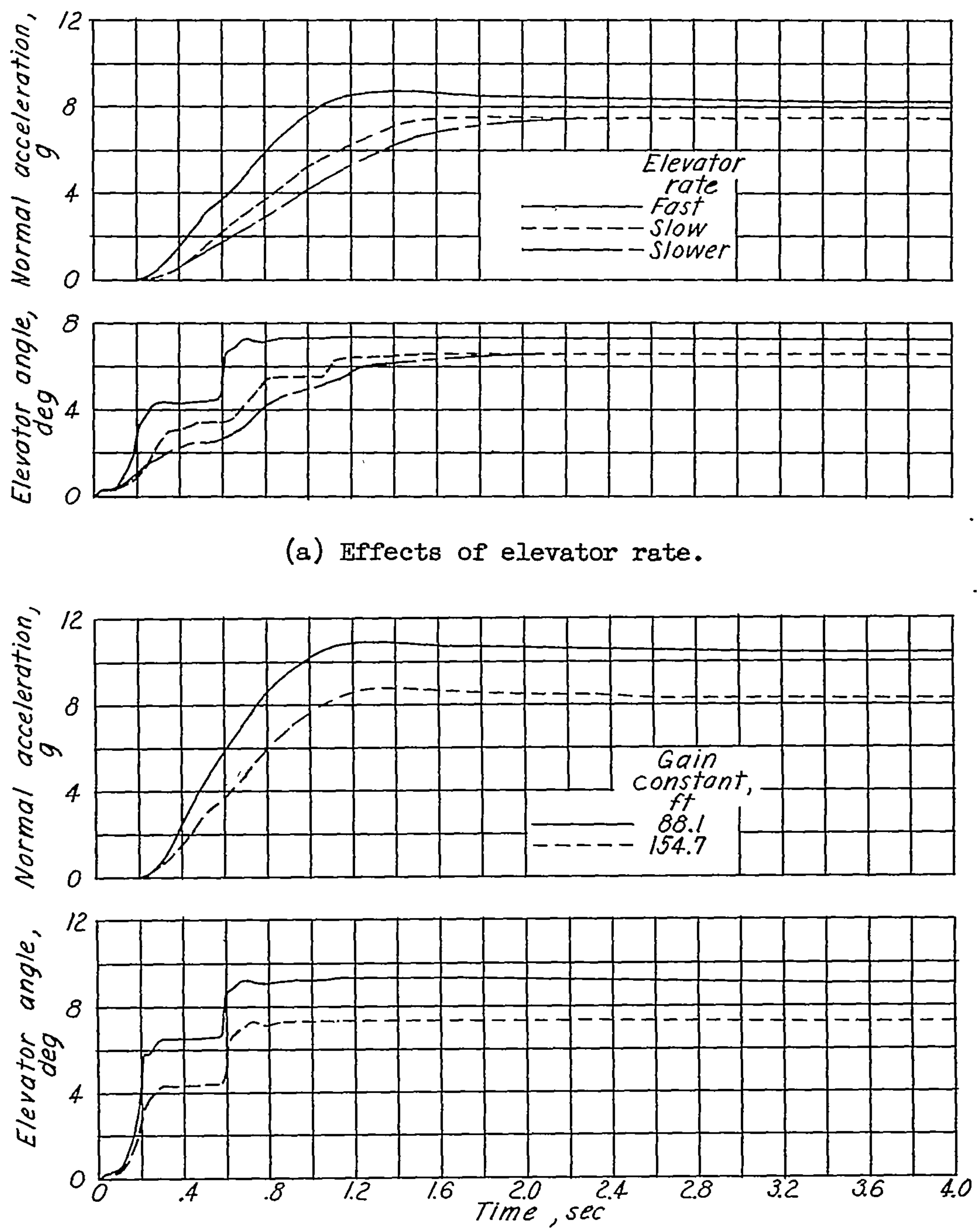


Figure 4.- Effects of control-stick inertia on the response of the airplane with the acceleration restrictor controlled by the signal $a_n + \frac{K}{g}\dot{q}$. Static margin, 10 percent M.A.C.; airspeed, 600 feet per second; K = 154.7 feet.



(a) Effects of elevator rate.

(b) Effects of gain constant.

Figure 5.- Effects of elevator rate and gain constant on the response of the airplane with the acceleration restrictor controlled by the signal $a_n + \frac{K}{g}\dot{q}$. Static margin, 10 percent M.A.C.; airspeed, 600 feet per second; stick inertia, 0.24 slug-feet^2.

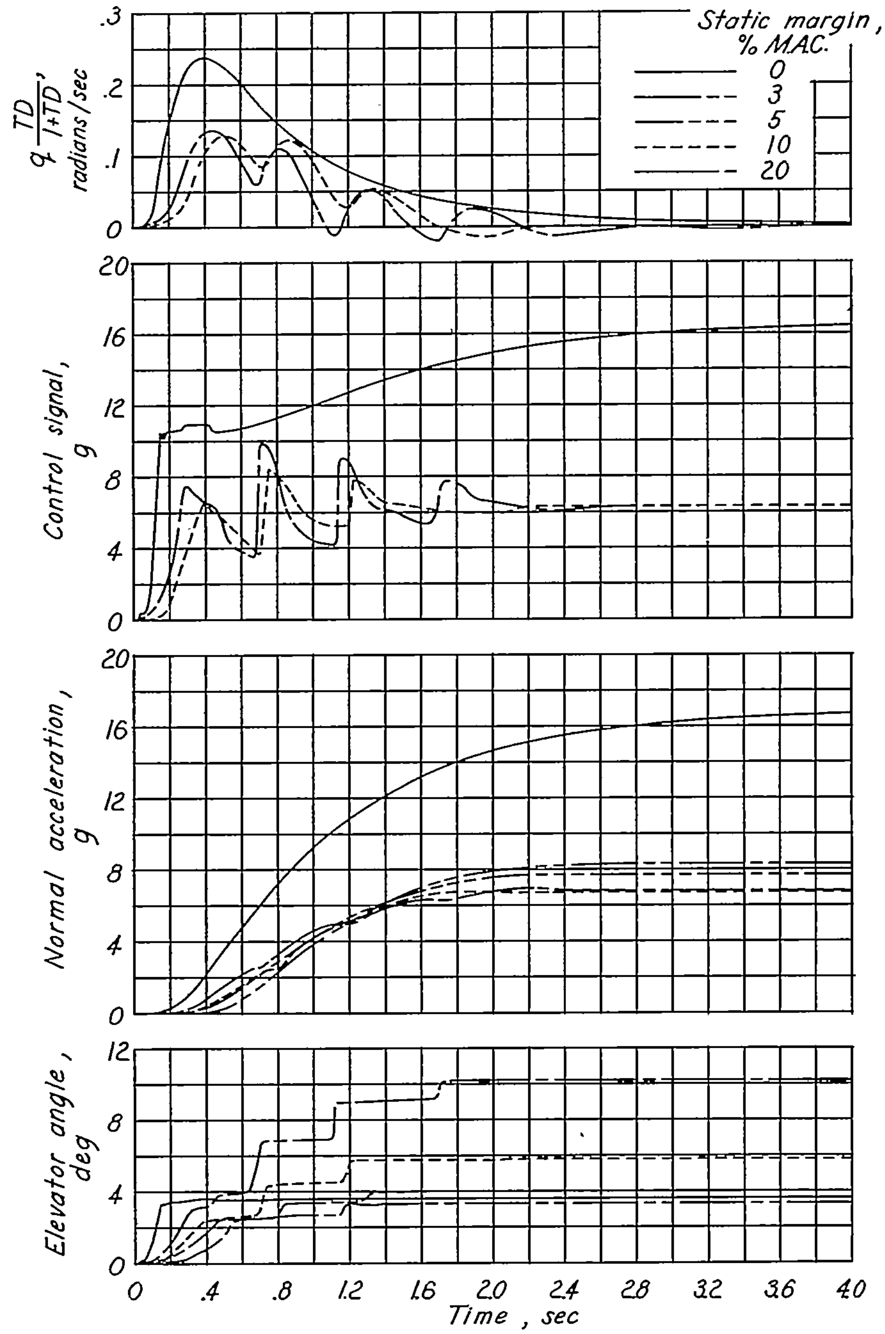


Figure 6.- Effects of static margin on the response of the airplane with the acceleration restrictor controlled by the signal $a_n + \left\{\begin{matrix}\frac{K}{g}\dot{q} \text{ for } \dot{q} > 0 \\ 0 \text{ for } \dot{q} < 0\end{matrix}\right\} + \frac{K_1}{g} q \frac{TD}{1 + TD}$. Airspeed, 600 feet per second; stick inertia, 0.24 slug-feet^2; $K = 154.7$ feet; $K_1 = 644$ feet per second; $T = 0.25$ second.

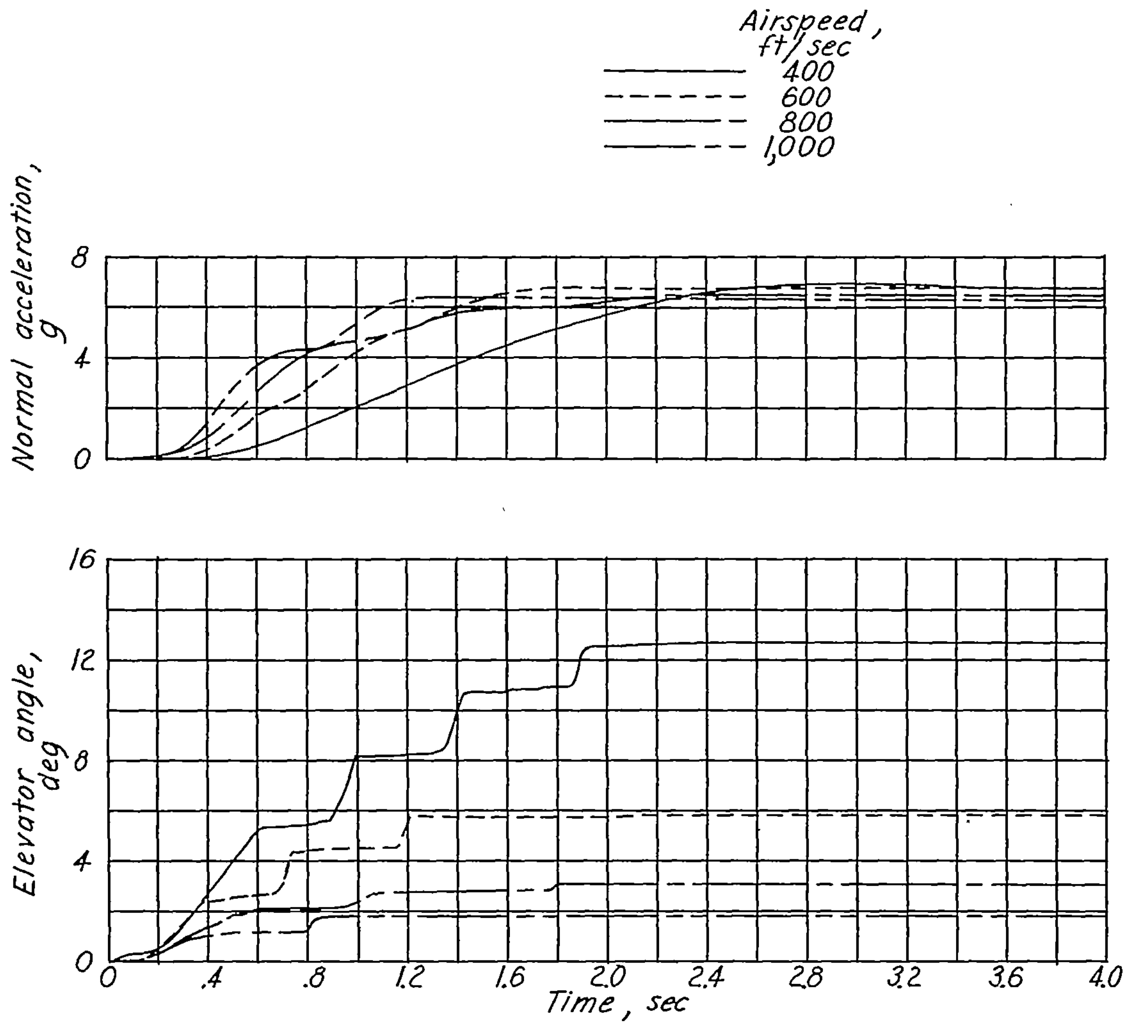


Figure 7.- Effects of airspeed on the response of the airplane with the acceleration restrictor controlled by the signal $a_n + \begin{Bmatrix} \frac{K}{g}\dot{q} \text{ for } \dot{q} > 0 \\ 0 \text{ for } \dot{q} < 0 \end{Bmatrix} + \frac{K_1}{g} q \frac{TD}{1 + TD}$. Static margin, 10 percent M.A.C.; stick inertia, 0.24 slug-feet^2; K = 154.7 feet; K_1 = 644 feet per second; T = 0.25 second.

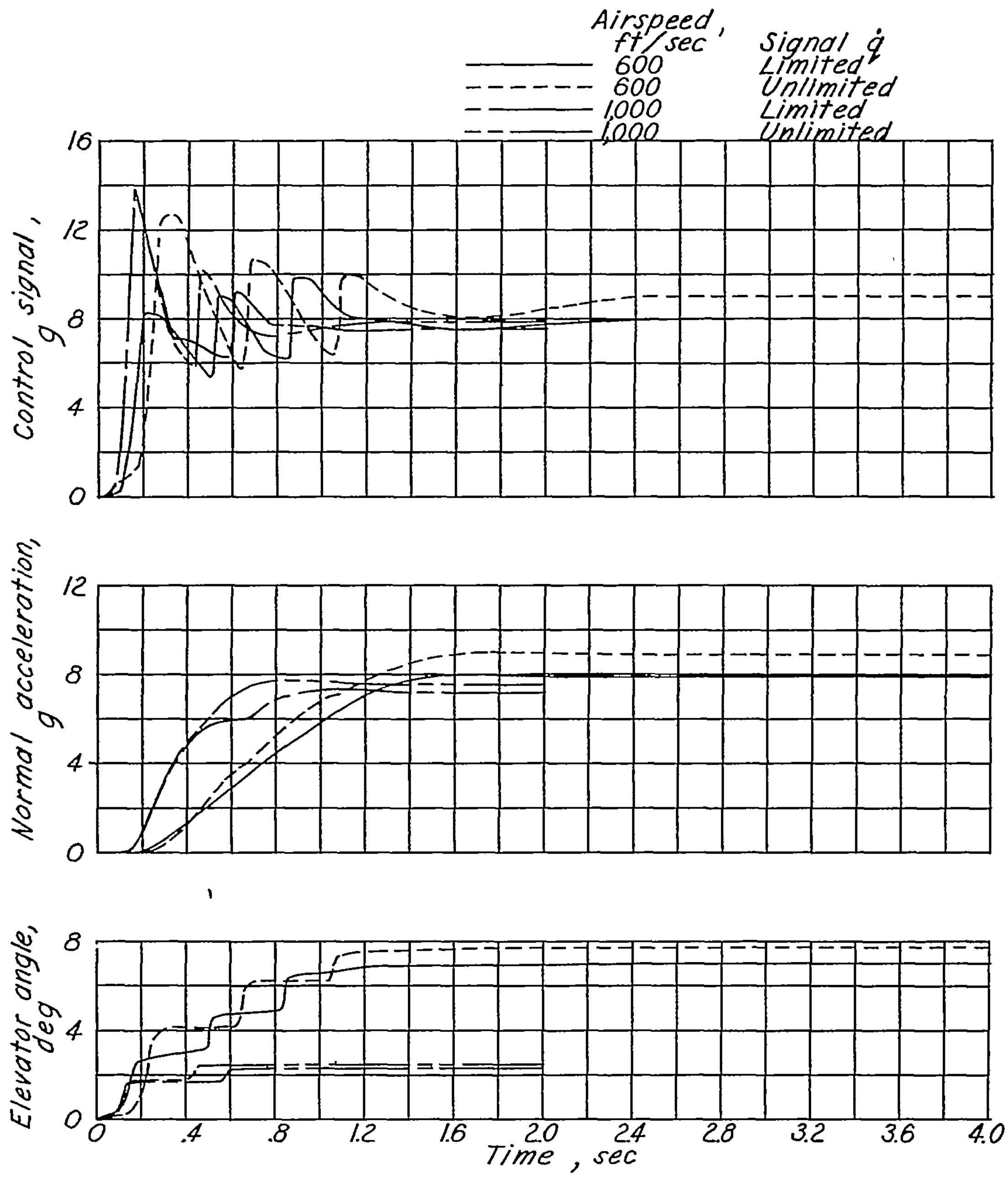


Figure 8.- Comparison of the response of the airplane with the acceleration restrictor controlled either by the signal $a_n + \frac{\dot{q}}{g}(K + K_1T)\frac{T_1D + 1}{TD + 1}$ or by the signal $a_n + \begin{Bmatrix} \frac{K}{g}\dot{q} \text{ for } \dot{q} > 0 \\ 0 \text{ for } \dot{q} < 0 \end{Bmatrix} + \frac{K_1}{g} q \frac{TD}{1 + TD}$ at two values of airspeed. Static margin, 10 percent M.A.C.; stick inertia, 0.24 slug-feet^2; $K = 154.7$ feet; $K_1 = 644$ feet per second; $T = 0.25$ second.

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